Energy Conversion and Management 191 (2019) 39–54

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Computational comparison of a novel decentralized photovoltaic district heating system against three optimized solar district systems

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ARTICLE INFO

Keywords:
District heating community
Solar energy
Photovoltaic based decentralized heating system
Techno-economic comparison
High latitude climatic conditions
Payback period

ABSTRACT

Climate change is one of the biggest challenges at the present time, and to tackle such issue, solar energy and efficient buildings, in general, can be used. The goal is to design and optimize photovoltaic based decentralized district heating system and later compare it—economically and technically—against three different optimized typologies of solar district heating system in Nordic conditions. The photovoltaic based decentralized system consists of one centralized low temperature tank charged by photovoltaic and air-water heat pumps and a borehole thermal energy storage, while the decentralized high temperature tank charged by an individual water-water heat pump in each house. The centralized warm tank charges the borehole thermal energy storage. The other three systems are photovoltaic based centralized, roof-mounted solar thermal based centralized and roof-mounted solar thermal based decentralized district heating systems. In solar thermal based systems, collectors are used to directly charge the short-term storage tanks instead of the photovoltaics/heat pump combination. The proposed system is simulated using TRNSYS software. Lastly, purchased electricity and life cycle costs of the system are minimized using multi-objective optimization and the genetic algorithm. The results indicated that the decentralized photovoltaic based system outdoes all the other systems in terms of techno-economic performance. The purchased electricity can be reduced by 22% while at the same time life cycle cost can be reduced up to 40%, compared to the worst optimized system (solar thermal based centralized system). Moreover, the decentralized photovoltaic based energy system has a payback period of 9–27 years, compared to the solar thermal based system and the conventional single building-heat pump system, i.e. around 17–58 years and 15 years, respectively. The highest renewable energy fraction for heating can be close to 99% for this system. The decentralization and electrical based district systems are better in terms of life cycle cost, payback period and in terms of technical performance, compared to traditional single house and solar thermal based district heating systems.

1. Introduction

The use of fossil fuels for energy production has caused large emissions due to which climate change phenomena can be observed. The cost of the fuel and energy has increased due to the increase in the demand and decrease in the supply. With the increase in the demand and consumption, the emissions have also increased which has significantly impacted the environment [1]. Because of the issue of climate change and global warming, the world has been looking to find other sustainable solutions. Generally buildings are the largest consumer of energy and emitters of CO_2. In Nordic countries buildings represents around 40% of the total energy consumption [2]. Therefore building sector is one of the major sectors that need to transform into a sustainable sector and decarbonize it.

The European Union (EU) has set a 20–20–20 target, the goal are to reduce emission, increase the renewable energy and reduce the emissions by 20% by 2020 [3]. Solar energy is the largest and most attractive renewable resource that is available [4]. Therefore, the conversion technology of solar energy into useful energy has a huge market potential. In Europe there are multiple solar district heating systems with collector areas ranging from 1000 m^2 to 156 694 m^2 [5] Moreover, the annual solar radiation received in the southern areas of Finland is around 900–1170 kW h/m^2 [6,7], therefore solar energy can be utilized in Southern Finland area. However, the major reasons why solar energy market is still under developed in Finland are: (1) the seasonal mismatch and (2) economical feasibility issues [8].

The diurnal behaviour of the solar energy is a significant problem for solar electric and thermal systems because of the hourly mismatch

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https://doi.org/10.1016/j.enconman.2019.04.017
Received 17 January 2019; Received in revised form 3 April 2019; Accepted 5 April 2019
Available online 09 April 2019
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between energy demand and generation and the high cost of storage. Tank storage or exporting heat energy to the grid [9] can solve the hourly solar electricity mismatch problem [10]. The issue with the tanks are that they can solve the mismatch problem for the days or few hours and that export prices are much lower than self-consumption value. The issue becomes significant when there is seasonal mismatch—when the heating demand is highest and the solar generation is lowest in winter. On the other hand, during summers, the heating demand is lowest while the availability of solar energy is quite significant. Therefore, the application of solar-based technologies has certain limitations in high latitudes [11].

Many solar based communities have been built in real, for instance in Germany [12], Sweden [13], Denmark [14] and Canada [15], to develop carbon neutral district networks. It is found that the community scale solutions and seasonal storage can resolve the issue of mismatch [16] and cost [17], in contrast to the single house solution. A constant load profile exists in district network, compared to individual building load profile [18], therefore community approach is reasonably better compared to single building heating system. Moreover, district sized energy systems can meet the demand of the buildings with similar emissions compared to single house system, but with lower total discounted cost [19]. District approach can also reduce the payback period [20]. However, seasonal storage is required to provide heating energy to the communities throughout the year. The energy can be stored in the seasonal storage during the summer and can be used in winters. The district heating systems has been built for multiple applications, for example for the commercial area [21] and also for the residential area [22]. Therefore, system has to be designed based on the available resources, storage and applications.

The earlier studies showed that, by using solar based district heating network, the performance of the system can be improved. Simulation studies shows that using solar based heating systems has higher efficiency and lower costs compared to the traditional electric heating systems. It is found that solar heating systems can meet up to 80–90% of the demand of the building during summer and 50% demand during winters [23]. Another study shows that solar heating district network integrated with the heat pump can perform better compared to heating network without solar energy [24]. In cold region of China, a pilot scale project showed that 60% of the heat demand of the building can be met via solar energy [25]. Some experimental studies carried out in Friedrichshafen, Neckarsulm, Rostock, Crailsheim in the central Europe regions showed that solar based district heating systems can meet 30–60% of the heating demand via solar energy and storage integration [16], In the cold climate, a pilot solar district heating system is built in 2005, at the Drake Landing Solar Community (DLSC), Canada. The district consists of 52 houses, these houses are provided with space heating via solar energy. It is found that this solar district heating can provided up to 98% of the space heating via solar energy [26]. In Finnish context during 1980s a solar district heating system was built in southern Finland, Kerava [27] and Eko-Viikki [28], however the system is able to meet up to 10% of the heat demand via solar energy. Nevertheless, this district failed to perform due to the issues of design, and storage. Therefore, further holistic research is needed to make such systems high performing and low-cost energy systems [29].

There are many different types of storages for long term storage for instance, chemical [30], latent heat [31] and sensible heat storage [32]. The sensible heat storage is cheaper and mature technology for seasonal storage [33], therefore same concept is used in the present study. For sensible seasonal storages there are multiple technologies such as hot water tank thermal energy storage (TTES), aquifer thermal energy storage (ATES), water pit thermal energy storage (PTES) and borehole thermal energy storage (BTES) [21]. The traditional hot tanks cannot be used for large term storage due to higher costs, higher heat losses and inability to operate on a large time scale [34]. Since the thermal energy storage (TES) stores energy in sensible form, the losses are significant. The thermal properties, shape, and volume of the TES are also important parameters that need to be designed in order to have better efficiency of the storage [35]. The large scale solutions allow better utilization of seasonal storage [16]. With the integration of seasonal storage the overall performance of the system can be improved. Terziotti et al. [36] in Virginia found that 91% of the energy can be provided by the solar thermal system when integrated with seasonal storage. Li et al. [37] found that monthly average solar fraction of 68% can be reached with solar thermal system integrated with seasonal storage in Beijing compared to a traditional space heating system. McDowell and Thornton [38] also found that with the integration of seasonal storage with the solar district heating system, the annual solar fraction of 98% can be reached in Canada. A simulation study in UK showed that by deploying seasonal storage, the solar fraction of 80% can be achieved [39]. Another study show, that by integration of the thermal energy storage with the cogeneration and hybrid energy system in district heating network, maximize the performance of the district sized energy system [40]. The integration of energy storage can also improve the flexibility of the cogeneration plant [41]. Overall, seasonal storage is an important component of the district heating systems. In the present study, BTES is used as seasonal storage, because of its simplicity of design, flexibility and favourable ground conditions in the surroundings [8].

One way to improve the technical performance of the solar based district heating system is to reduce the operating temperature of the network, as this helps to reduce the losses through the distribution network and storage [42]. In the future, the low temperature district heating network may play important role in reducing carbon emissions from the heating networks as discussed by Lund et al. [43] and by Schmidt [44]. This low temperature can be increased with the help of heat pump (HP). Traditionally heat pumps are used without solar energy integrated with the ground source heat pump and buildings [45]. However, with the integration of solar energy and seasonal storage with the heat pump, the performance of the heat pump, i.e., coefficient of performance (COP) can be increased [46]. When solar charged seasonal storage is integrated with the heat pump, the HP evaporator temperature increases due to which the COP of the heat pump also improves [47]. Different strategies, architectures [48] and heat pump types can be used in the district network [47]. For example the heat pumps can be brine-water or air-water heat pumps. The distinct feature in the present study is to integrate both types of heat pumps for district application and to determine the overall performance.

The most common solar generation systems are solar thermal collector (ST) and solar photovoltaic panels (PV) [49]. These two systems can provide heating/cooling and electrical energy to the communities. Usually, solar thermal collectors are integrated to provide heating and cooling to the buildings [50]. On the other hand, PV can also be used to provide heating and cooling, other than to provide electricity to the buildings. By integrating PV with heat pump [51], the heating or cooling energy can be provided to the building. A study in central Europe showed that hybrid energy system, with collector, photovoltaic and district heating network provides benefits in terms of costs, emission reductions and sustainability [52]. Another study in Latvia showed that solar energy use in the district network would improve the overall performance of the conventional network [53]. Therefore, large PV based district heating system integrated with air-source heat pump can provide heating energy to the communities [10]. In Finland, since there is no feed in tariff [54] and export price of the electricity is very low, the excess energy from the PV can be stored in the seasonal storage for later use during winters instead of exporting it to the grid. Storage can increase the onsite energy fraction of the PV in the community. The challenge lies whether electrical storage or heat storage is beneficial. It is found that electrical storage can be expensive compared to the heat storage [55]. Therefore, the excess electricity produced by the PV can be stored in the tanks by converting it to the heat energy. This would improve the economics and self-consumption capability of the community. Moreover, municipalities' support and pilots projects are

needed to develop such solutions in Finland [56]. In addition, there is a lack of studies and evaluations where heat-pump and PV-integrated systems are studied in detail [57] for community scale application in Nordic conditions. Therefore, solar electricity (PV) based district heating systems are designed and analysed, both technically and economically, in the present study and compared against the solar thermal based systems.

There are many analysis methods and solutions selection criteria used by researchers to evaluate and compare different solar based energy systems. Many researchers have used purchased energy [41], life cycle costs [58], solar fraction [14], emissions [59], onsite fraction and matching [60], storage efficiency [10] etc. All these criteria can be used to justify certain system selection, depending on the objective of the decision makers. The basic main criteria used by the companies and decision makers are payback period, costs and efficiency of the system [61]. Therefore, the scope of the study is limited to these factors and analysis methods, which are mainly used to compare and analyse the systems in the present study.

The novelty of the present study lies in (1) introducing a fully new type of decentralized PV based district heating system, (2) optimizing the mentioned system technically and economically, and (3) comparing its performance both technically and economically with three other optimized new systems—for Nordic conditions. These four systems can be grouped into two systems based on the distinct renewable technology used, i.e., 1) photovoltaic based solar district heating system and 2) roof-mounted solar thermal based solar district heating system. In addition to that, each of the two systems is further divided based on discrete features of the distribution and storage layout—centralized and semi-decentralized. The centralized and decentralized roof-mounted solar thermal based [17] and centralized photovoltaic based district heating systems [10] have already been simulated and studied in earlier publications. In the present study, the decentralized photovoltaic based district heating system is designed, optimized and lastly compared to all of the previous three systems.

The research objective and aim of the present study is to design, compare and propose an optimized (both economically as well technically) novel community sized district heating system that can meet the demand of the community, built in Nordic conditions. Purchased electricity and life cycle costs (LCC) are the two objectives that are minimized. Moreover, the heating renewable energy fraction (REF), a simple payback period and onsite energy fraction (OEF) for each system are the other three criteria calculated and compared to provide techno-economic performance comparison and a complete picture to the stakeholders. All these methods are used because these are widely used methods for analysis of such systems in the scientific studies [17,10].

2. Methodology framework

The methodological principle of the investigation is to compare the presented systems on the basis of two primary parameters (objective functions), one representing the technical performance (purchased electricity) and the other representing the economic feasibility (life-cycle cost, LCC). Multi-objective optimization is used to minimize these parameters simultaneously. As these parameters are conflicting with each other, there is not only one optimal solution but a set of optimal solutions, so called Pareto set. Additional to these primary parameters, three secondary indicators, Simple payback period (SPP), Renewable energy fraction (REF) and Onsite Energy Fraction (OEF) are calculated from the optimized solutions. Secondary indicators are not participating in the optimization process but are just post-processed from the optimized solutions. The systems simulation models on TRNSYS are explained in Section 3, the multi-objective optimization method is explained in Section 4 and the other performance indicators calculation method is explained in Section 5.

3. Methodology: system description and simulation method

The systems cases are designed on TRNSYS simulation software [62]. Later on these systems are multi-objective optimized using MOBO (multi-objective building optimizer) [63]. The details of the simulation method and optimization methods are provided in the following sections.

3.1. Description of the investigated cases

The study is done on a simulated Finnish community with dedicated solar based district heating systems. There are 100 houses in the community with 100 m^2 of heated area each, the details of the building envelope is provide in [48]. Overall, in the system proposed below, solar photovoltaic panels are used to produce electricity and heat, and then this heat is stored in the tanks. Borehole thermal energy storage (BTES) is used to store surplus energy. The control strategy of the photovoltaic based decentralized system is described in detail in the paper. In addition to the above-mentioned energy system, three distinct community-scale solar district heating systems and a reference case are also introduced to compare all the systems and a reference system economically and technically, against the proposed photovoltaic based decentralized system for cold climate in the paper. All the four systems are new and optimized systems, while the reference case is non-optimized. The four solar district energy systems and reference system are as follows:

1) Case 1: Decentralized photovoltaic based district heating system (DPV), optimized new system.
2) Case 2: Centralized photovoltaic based district heating system (CPV), optimized new system [10].
3) Case 3: Decentralized roof-mounted solar thermal collector based district heating system (DST), optimized new system [17].
4) Case 4: Centralized roof-mounted solar thermal collector based district heating system (CST), optimized new system [17].
5) Non-optimized reference case, single building system.

The three systems (CPV, DST and CST) have been optimized in previous studies and this study is reusing those results. The expressions ‘centralization’ and ‘decentralization’ are used to describe the district heating systems typologies. Here the centralized system means the generation, distribution, short-term storage and seasonal storages are centralized. In a decentralized system, the generation, low-temperature network and seasonal storage is centralized, while the domestic hot water and a high temperature network are decentralized [17].

In the present study, a new type of decentralized photovoltaic based district heating system is designed, optimized and analysed. The CST, DST [17] and CPV [10] have been optimized and studied earlier and used in the present study for comparison only against the proposed decentralized photovoltaic based district heating system. Their control strategies have also been explained in earlier studies [17]. Table 1 shows the main components and products of the optimized DPV, CPV, DST, CST systems and a non-optimized reference system. The layout and control strategies are discussed in the next sub-section.

3.1.1. Decentralized photovoltaic based district heating system (Case 1, DPV): method and controls strategies

This system is inspired by the decentralized solar thermal collector based district system [17]. However, the difference lies in the generation technology i.e., PV is used as the main source of energy generation and in the control strategy of the heat pumps. The schematic representation of decentralized photovoltaic based energy system is shown in Fig. 1. The energy system (DPV) consists of the following:

- A central photovoltaic panels (PV) field is used to run the centralized air-water and distributed water-water heat pumps,

Table 1
The main components of the optimized DPV, CPV, DST, CST systems and the non-optimized reference system.

Components	DPV, Case 1	CVP, Case 2	DST, Case 3	CST, Case 4	Reference case
Photovoltaic panels	Yes	Yes	Yes	Yes	No
Roof-mounted solar thermal collectors	No	No	Yes	Yes	No
Air-water heat pump (NIBE-F2120) [64]	Yes	Yes	No	No	No
Water-water heat pump (NIBE-F1345) [65]	Yes	Yes	Yes	Yes	Yes
Hot tank volume	Decentralized	Centralized	Decentralized	Centralized	Yes
Warm tank volume	Centralized	Centralized	Centralized	Centralized	No
Seasonal storage	Yes	Yes	Yes	Yes	No

- A centralized large warm tank,
- Decentralized small hot tanks present in each house,
- Centralized warm tank is charged via centralized air-water heat pumps (AW-HP), and decentralized hot tanks are charged via the distributed water-water heat pumps (WW-HP) during summer,
- Borehole thermal energy storage (BTES) is charged by the warm tank only, in case of extra heat energy,
- Decentralized water-water heat pumps (WW-HP) are used to heat the decentralized hot tanks, while the warm tank is charge via BTES in case of unavailability of solar energy,
- Space heating (SPH) is provided mostly from the central tank,
- Domestic hot water (DHW) is provided through the distributed hot tank.

In this system, solar photovoltaic panels (PV) are used as the main energy source to generate heat by running the heat pumps. The electricity produced by PV is initially used to run the appliances in the buildings, after that, the remaining electricity is used to the heat pumps to charge the short-term tanks. First, the water-water heat pump (WW-HP) is activated to heat the hot tank and then excess electricity is used to operate the AW-HP to heat the warm tank. If there is any excess electricity produced by the PV after using it in the appliances and heat pumps, it is sold to the grid. Any shortfall of electricity is met via grid while excess is exported to the grid, while all the heating demand is provided through the local grid.

The centralized air-water heat pump (AW-HP) is used to charge the centralized warm tank at 40 °C. Any excess energy is transferred to the boreholes from the centralized warm tank if the temperature is 5 °C higher than the average temperature of the BTES ground storage. The decentralized water-water heat pump (WW-HP) present in every house is used to heat to decentralized hot tank at a higher temperature i.e. up to 60 °C, taking energy from the space heating return line. The centralized warm tank serves as the main source to provide the space heating (SPH) as the SPH network is centralized. The domestic hot water (DHW) is provided via decentralized hot tank. The domestic hot water is provided at 58 °C and the space heating is provided between 27 °C and 40 °C, depending on the outside ambient temperature [66]. A direct electric heating system is also provided in case of any shortfall in the heating temperatures. A schematic representation of this system is shown in Fig. 1.

3.1.2. Centralized photovoltaic based district heating system (Case 2, CPV): method and controls strategies

The centralized photovoltaic based district heating system (CPV) has centralized warm and hot tanks charged by the PV. The electricity from PV is first used to run appliances, then heat pumps and any excess is exported to the grid. The centralized air-water heat pump (AW-HP) charges the centralized warm tank, while the centralized water-water heat pump (WW-HP) charges the centralized hot tank at higher temperature. The space heating is mainly provided by the warm tank and

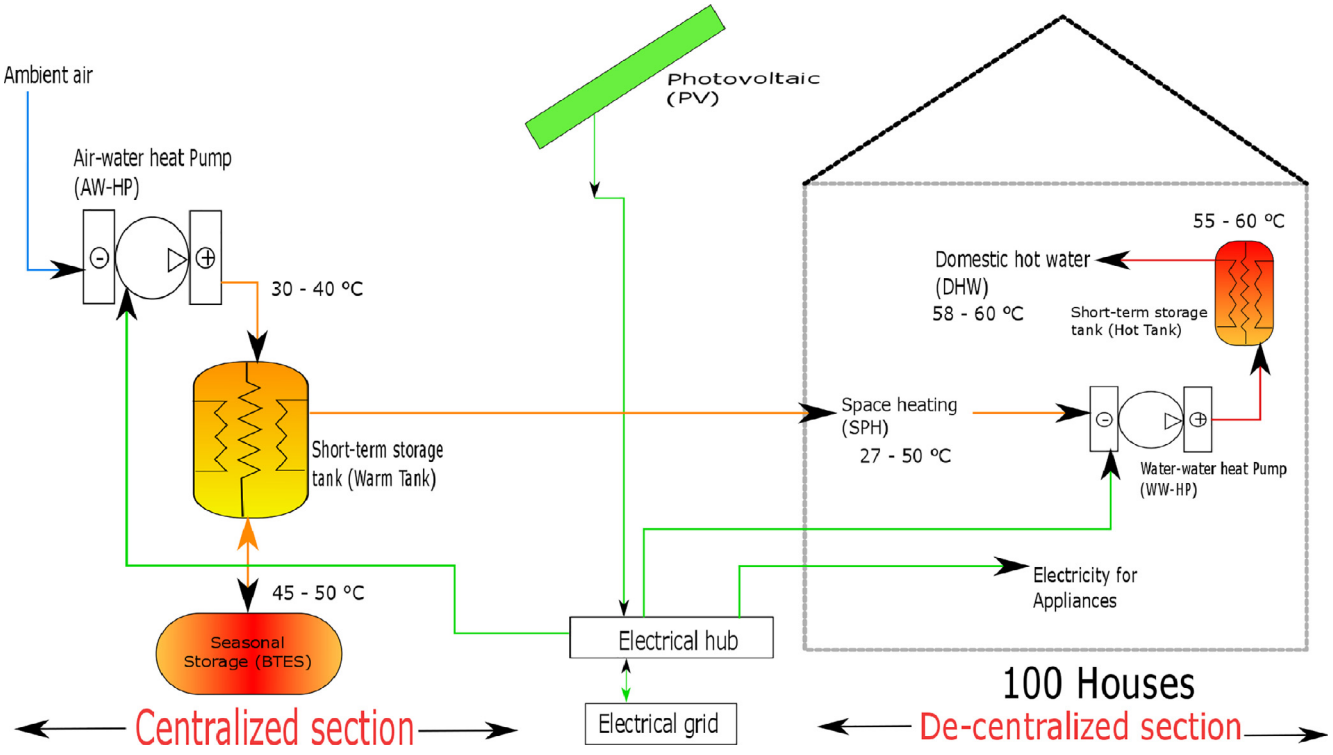

Fig. 1. Simple schematic representation of the decentralized photovoltaic based district heating system (DPV).

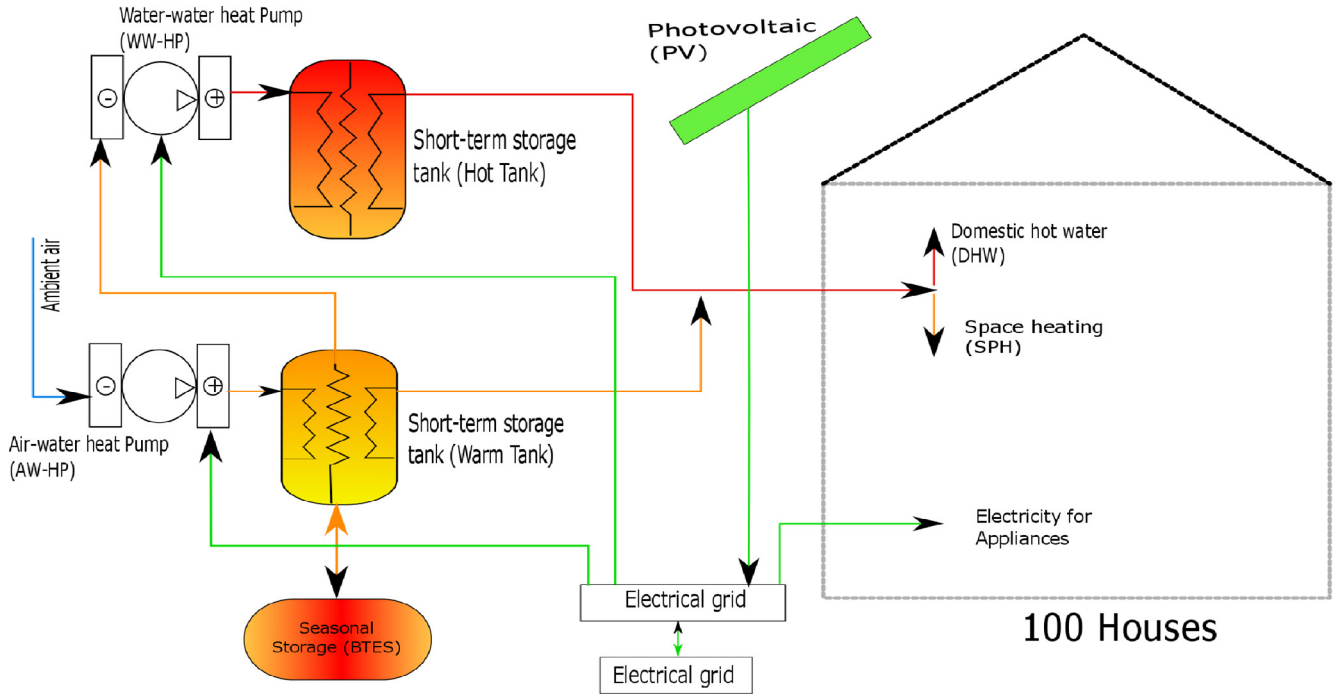

Fig. 2. Simple schematic representation of the centralized photovoltaic based district heating system (CPV) [10].

domestic hot water is provided by both the warm and hot tanks. The excess energy from both the short-term tanks is transferred to the boreholes thermal energy storage (BTES). During winters, when solar energy is not available the energy provided by the BTES and heat pump similar to the DPV system described above. The detailed designs and controls of the CPV system is described in earlier study [10]. A schematic representation of this system is shown in Fig. 2 [10].

3.1.3. Decentralized roof-mounted solar thermal collector based district heating system (Case 3, DST): method and controls strategies

The decentralized solar thermal based district heating system (DST) has centralized warm tank charged by the collectors, instead of the PV. The collector is used to charge the warm tank directly, while the hot tank and water-water heat pumps (WW-HP) are decentralized and present in each house. The decentralized hot tank is charged by the decentralized WW-HP present in each house by taking energy from the space heating return line. The space heating is mainly provided by the centralized warm tank and domestic hot water is provided mainly by the decentralized hot tanks in each house. The excess energy from the short-term warm tank is transferred to the boreholes thermal energy storage (BTES). During winters, when solar energy is not available the energy provided by the BTES and heat pump. PV is used only to provide the electricity to the system and the appliances. Import and export of electricity is carried out via grid to meet the shortfall or to sell the excess electricity from the PV. The detailed designs and controls of the DST system are described in earlier study [17]. A schematic representation of this system is shown in Fig. 3 [17].

3.1.4. Centralized roof-mounted solar thermal collector based district heating system (Case 4, CST): method and controls strategies

The centralized solar thermal based district heating system (CST) has centralized warm and hot tanks charged by the collectors, instead of the PV. The collector is used to directly charge both the tanks based on the set points. The excess energy from both the short-term tanks is transferred to the boreholes thermal energy storage (BTES). During winters, when solar energy is not available the hot tank is charged by the water-water heat pumps (WW-HP) and warm tank is charged by the BTES. The space heating is mainly provided by the centralized warm tank and domestic hot water is provided mainly by the centralized hot tanks in each house. PV is used only to provide the electricity to the system and the appliances. Import and export of electricity is carried out via grid to meet the shortfall or to sell the excess electricity from the PV. The detailed designs and controls of the CST system is described in earlier study [17]. A schematic representation of this system is shown in Fig. 4 [17].

3.2. Single building, non-optimized reference case

In order to provide a reference scenario and business as usual case a reference case is also used. This case consists of a typical heat-pump-heated modern building in the same climatic environment as the investigated cases. It consists of a detached building with 100 m^2 area integrated with a 3 kW heat pumps in the Finnish climate. No seasonal storage or solar energy generation technology i.e. collector or photovoltaic is integrated. The space heating demand of the house is 25 kW h/m^2/yr, a domestic hot water demand of 35 kW h/m^2/yr, and appliances demand of 40 kW h/m^2/yr. Moreover, the building has a tank of 1 m^3 to store heat energy. This building has the heat pump that is used to charge the tank. The purchased electricity is used to run the system and it's auxiliary.

3.3. Simulation: TRNSYS

Dynamic simulation software (TRNSYS) [62] is used for the simulations of the proposed district heating system described above. This simulation software has been used and validated by Drake Landing Community, Canada for similar application [15]. TRNSYS modules are used for the modelling of roof-mounted solar collector (Type 1b), weather data (Type 15), short-term tanks (Type 543), heat pump (Type 668), borehole thermal energy storage (BTES) (Type 557a) and photovoltaic panels (Type 194) [48]. The technical properties of the collectors and photovoltaics are defined in Table 2. TRNSYS modules for the controls of the pumps (Type 2b), heat pump (Type 2b) and temperature (Type 11f) are used. These are basic on/off controllers which operate based on the temperature as described in sub-Section 3.1 of the paper. These input parameters have already been defined in [48]. In the

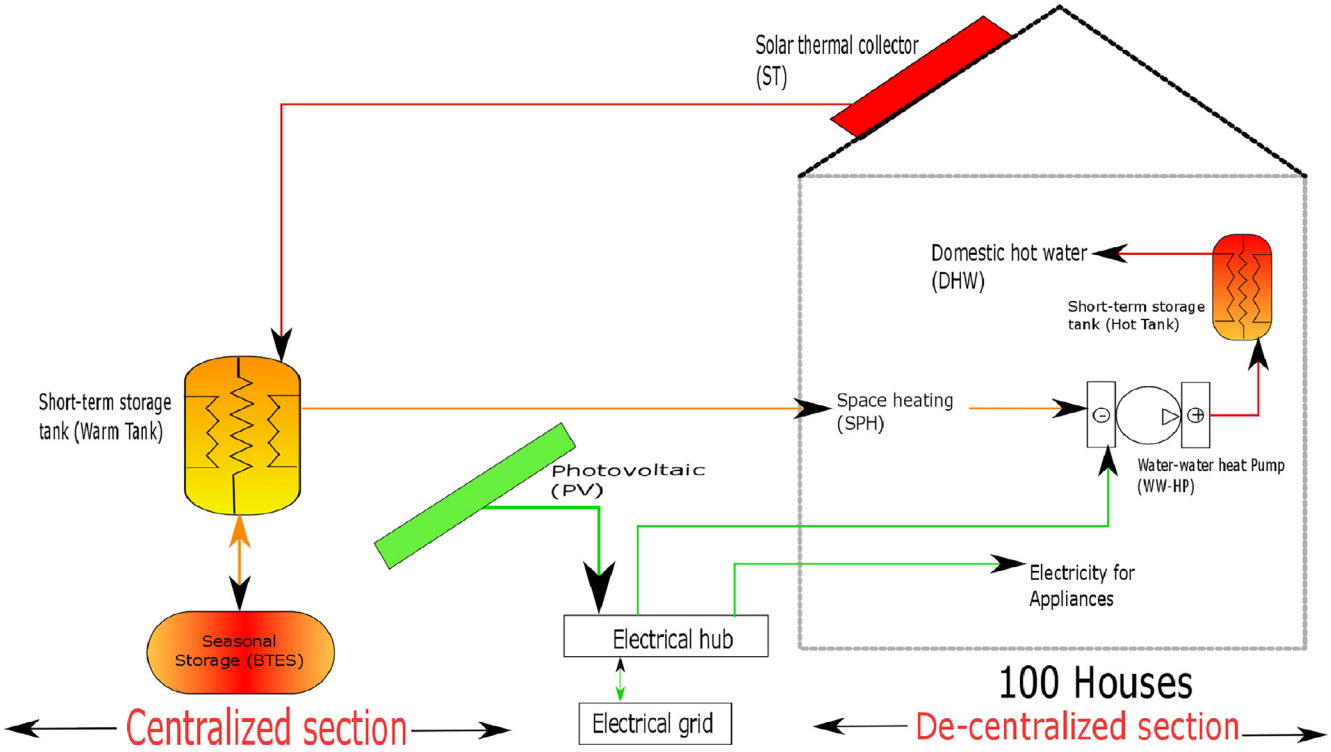

Fig. 3. Simple schematic representation of the decentralized roof-mounted solar thermal collector based district heating system (DST) [17].

present study, a decentralized photovoltaic based district heating system is designed and optimized. Later on, all four systems and reference case are compared against each other to propose a technically and economically feasible solution.

3.4. Weather, solar radiations and demand profiles: TRNSYS

The Southern Finland weather data is used in TRNSYS [48]. The annual hourly solar radiation and outdoor temperature are shown in

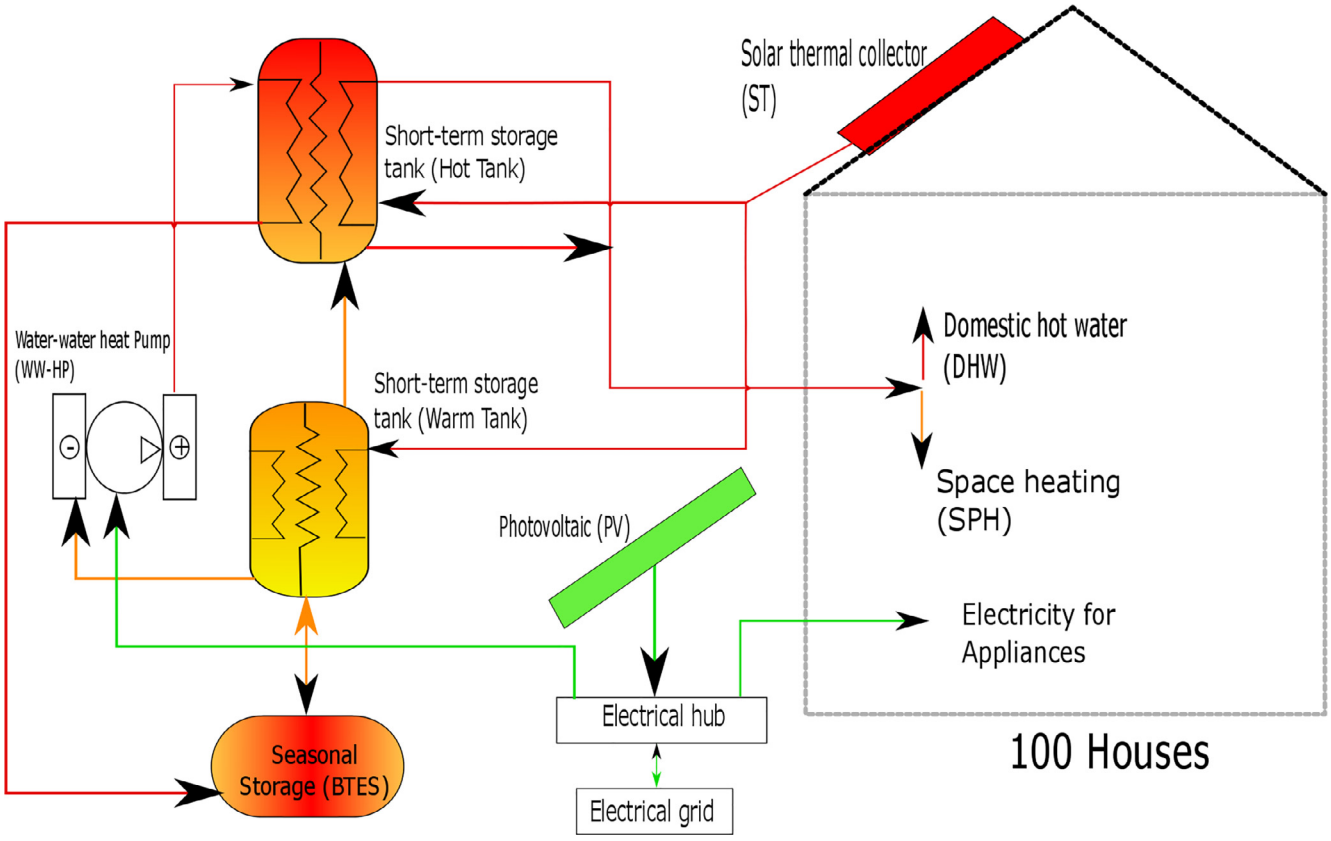

Fig. 4. Simple schematic representation of the centralized roof-mounted solar thermal collector based district heating system (CST) [17].

Table 2
The properties of the roof mounted solar collector and photovoltaic panels.

Components	Technical properties	Reference
Photovoltaic panels	Tilt angle = 50°; Peak efficiency = 15.37%	[67]
Roof-mounted solar thermal collectors	Tilt angle = 50°; Intercept efficiency = 0.878; efficiency slope = 3.35 $W/m^2 k$; efficiency curvature = 0.026 $W/m^2 K^2$	[68]

Fig. 5a [69,48]. The total annual solar radiation on the horizontal surface is 969 $kW/m^2/yr$ [69,48]. The monthly space heating demand (37 $kW h/m^2/yr$) and domestic hot water demand (35 $kW h/m^2/yr$) is shown in Fig. 5b [58].

4. Methodology: optimization

The motivation to use multi-objective optimization approach compared to the other methods (without optimization) is because with huge number of possible designs offered; a trial and error method cannot find optimal solutions while an exhaustive search is an inefficient exploration procedure in time and effort. Moreover it is difficult to design systems without optimization, because of the complex interaction between different system components, such as the buffer storage, seasonal energy storage and variable solar energy generation system. Sizing of one component can affect the operation of another component in unpredictable ways. Hence, simulation based optimization approach has been used to find the solutions, instead of the other methods mentioned above.

In general, two objectives such as costs and energy performance can be minimized by using simulation based optimization method. These objectives are selected in such building energy efficiency scenarios because, in high technical performing cases, less energy is needed to be imported but the costs are higher and vice versa. Moreover, purchased electricity is also the only type of external energy (no outside district heating connection), so it can be used as a measure of the total efficiency, since all heat losses are included already. These two objectives i.e. imported electricity and costs are conflicting in nature and do not follow same development direction. In this way a Pareto optimal front is generated containing hundreds of non-dominated possible solutions [17]. Using single objective or non-optimization approach would give only one solution and it is possible that this solution may not be the optimal solution as well. However, it is possible that this one solution would lie on the multi-objective results (Pareto front) among hundreds of other optimal solution. Multi-objective optimization is giving hundreds of optimal solutions with different technical and financial performance. This method has been used in many previous published works such as in [58,70,71] and similar approach is used in the present study.

4.1. Optimization algorithm and TRNSYS simulation integration method

In the present study, the TRNSYS system models and multi-objective building optimizer (MOBO) are combined to perform the optimization. For this study, the NSGA-II algorithm is used, because it can take care of the constraints, discrete and continuous variables for a multi-objective problem. Furthermore, it allows parallel computing to save time [71]. The detailed study of this algorithm is provided by Deb at al. [71]. An initial population of 16 individuals and 300 generations is selected in MOBO [17]. The TRNSYS simulates the random design variables values provided by the NSGA-II algorithm, the results are then sorted by MOBO based on the objective functions [17].

The Fig. 6 shows the modelling, simulation and optimization logic and flow chart. The design variables values are generated by the MOBO optimizer, these values are then introduced in TRNSYS for simulation. The results from the TRNSYS are then evaluated and arranged by MOBO based on the objectives and criteria.

4.2. Problem setup

The objective and aim of the study is to design and optimize the decentralized photovoltaic based district heating system based on the given objectives and then compare this system against all the three different concepts—i.e., centralized collector, decentralized collector and centralized photovoltaic based district heating systems. Firstly, the decentralized photovoltaic based energy system is modelled and then optimized. Lastly, all the systems are compared to analyse the differences between the four optimized systems and a reference non-optimized case based on various criteria. The final purchased electricity, payback period, renewable energy fraction, and life cycle costs (LCC) are calculated to evaluate the system.

4.2.1. Objective functions of the multi-objective optimization

The objective function of the multi-objective problem is to minimize the purchased electricity and life cycle costs (LCC). These two objectives are selected because both the purchased electricity and LCC are of the interest of the stakeholders. Purchased electricity is a measure of the technical performance of the system and LCC is a measure of the economic. These two functions conflict with each other, which is a necessary feature in multi-objective optimization [71]. Furthermore, the payback period and renewable energy fraction are also calculated for each optimized cases to provide the most feasible and economical solutions.

The optimization problem is as follows:

$$\text{Min}\{G_1(x),\ G_2(x)\},$$

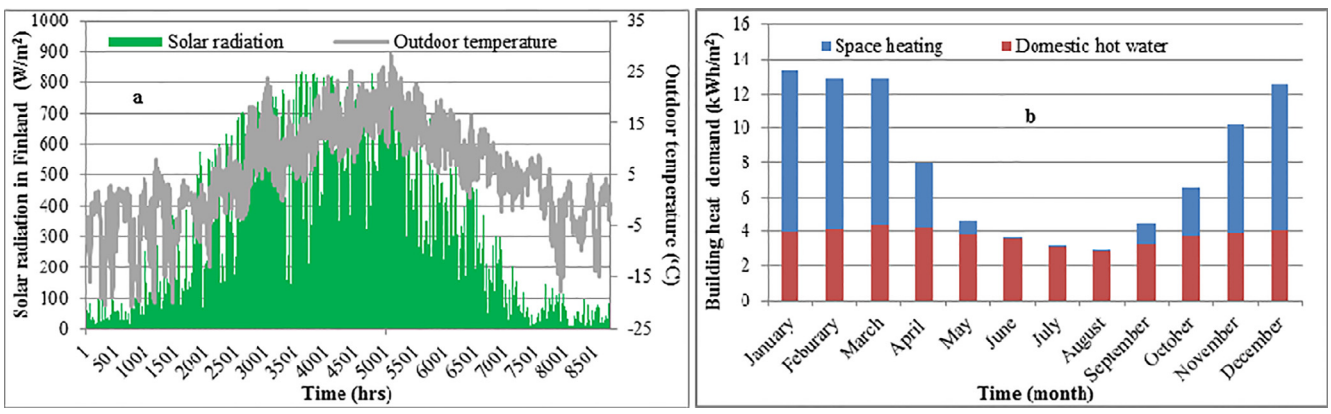

Fig. 5. The (a) Hourly ambient temperature and solar radiation; (b) monthly space heating and domestic hot water demand of the building.

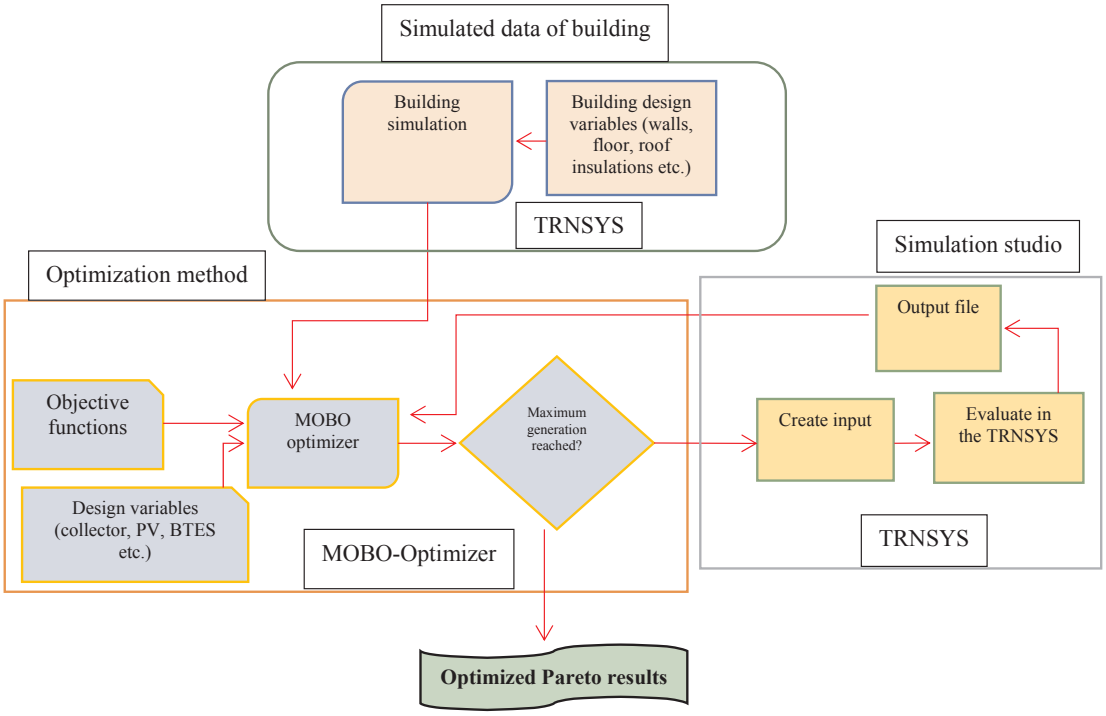

Fig. 6. Simulation and optimization methodology logic and flow chart [17].

for all $\boldsymbol{x} = [\boldsymbol{x}_1, \boldsymbol{x}_2, ...,\boldsymbol{x}_n]$,

where G_1 is the purchased electricity for the system together with the building appliances and G_2 is the life cycle costs of the system, and 'x' is the vector of the design variables (as defined in Subsection 4.2.2). In this problem, there are nine design variables that are considered and introduced in Table 3. LCC includes the investments and operation costs for 25 years. In the present study, import electricity price of 11.10 c/kW h and export electricity price of 4.04 c/kW h are used based on 2016–2017 electricity prices [72]. Due to the decreasing trend in the electricity price in the Nordic market, the price escalation rate of 1% is used [73] and 3% interest rate is used [74]. No disposal costs are included in the calculations [10].

4.2.2. Design variables and parameters

The design variables can be selected by the design engineer, depending on the importance and expertise. In the earlier studies, it is found that generation components such as collectors, PV and heat pumps can vary technical performance and cost of the systems [11,48,16]. After generation components, storage and demand can also play significant role in varying the performance of these systems [11,48,16]. As shown in Fig. 1, these are also the main components of the proposed energy system (DPV). Therefore, to include the impact of all the design variables and to provide a holistic behaviour, all the design variables are included in the optimization problem. Nine design variables are selected in this paper for optimization, namely: (1) photovoltaic area, (2) warm tank volume, (3) hot tank volume, (4) BTES volume, (5) building's configuration, (6) BTES aspect ratio, (7) BTES borehole density, (8) air-water heat pumps size and (9) water-water heat pump size. These variables are selected to provide a wide range of possible optimal solutions. The values or range of the design variables and the corresponding investment costs are shown in Table 3. The reference of the design variables and their values are from Drake Landing solar community, due to similar cold conditions [15]. However, to provide a broad range of possible optimized solutions, the range of the design variables are kept wide as shown in Table 3. Although systems are different, however, the baseline conditions for all the simulated systems are same, for instance, the costs, technical parameters, optimization conditions, demand profile and weather profiles are kept same in all the systems. It is done in order to provide close comparison between all the four optimized systems and the non-optimized reference

Table 3
Design variables used for the simulations and the corresponding investment costs of the components [17].

Design variables	Range of the values	Prices (€)	References
Roof mounted flatbed ST area (m^2)	500–6000	605–532 €/m^2	[75]
Polycrystalline PV capacity (kWp/house) on the ground/roof	1–30	450–200 €//m^2	[78]
Hot tank volume/house (m^3)	50–500	900–810 €/m^3	[75]
Warm tank volume (m^3)	50–500	900–810 €/m^3	[75]
Air-water heat pump (16 $kW_{thermal}$/unit each)	0–100	425 €/unit	[64]
Water-water heat pump (3 $kW_{thermal}$/unit each)/house	0–100	325 €/unit	[79]
BTES aspect ratio	0.25–5	33.5 €/m (drilling) + 3 €/m^3 (excavation for insulation) + 88€/m^3 (1.5 m insulation thickness)	[80,79]
BTES density (boreholes/m^2)	0.05–0.25		
BTES volume (m^3)	10,000–70,000		
Building type in each energy system	Heating demand = 25 kW h/m^2/yr	2973 €/building	
	Heating demand = 37 kW h/m^2/yr	605 €/building	[48]
	Heating demand = 50 kW h/m^2/yr	0 €/building	

case. Same values are provided in the MOBO optimizer for all the systems, while running the optimization and simulations together as shown in Table 3. However, during optimization the NSGA-II algorithm inside MOBO would select the optimal values of each design variable from Table 3, in order to minimize the life cycle cost and purchased electricity of the particular system under study.

Wide ranges of values are used for the variable to provide wide range of solutions and to find optimal combinations of the design variables. Table 3 shows constant price for some components, and variables price for some components. It is assumed that cost of the components goes down with increase in the size, due to economics of scale. The cost of the basic building is assumed to be '0' and any improvement in the building efficiency is given as the difference from this zero reference cost. Buildings are included in the optimization problem as a design variable in all the four systems and not separate scenario. Therefore the three buildings types based on their space heating demand (quality) are distributed on the same Pareto front of each energy system, depending on the cost and technical performance of that particular energy system. These buildings are selected by the optimization algorithm in order to optimize the techno-economic performance of the whole energy system. The collectors used in the study are roof mounted flatbed solar collectors which are expensive compared to ground mounted collectors [75]. Finnish market is still under development therefore higher prices can be assumed for the roof-mounted flatbed collectors, tanks and polycrystalline PV panels (including taxes). The PV is assumed to be installed on the ground at a centralized location (additional on the car garage roofs), a similar construction to that in Drake Landing Solar Community (DLSC) [15]. This is done to have large space available in order to reduce the purchased electricity from the grid. Moreover, empty land is available easily in Finland due to low population density [76]. The distribution piping length for domestic hot water for 100 buildings is around 4000 m for the centralized system and 400 m for the decentralized system [17]. The average cost of the piping used is 20 €/m [77]. The piping network is simulated using Type 709 [62] in the TRNSYS.

5. Techno-economic performance indicators

5.1. Motivation to use the indicators

In order to analyse the performance of the energy system, both the technical and economical performances are key elements to provide feasibility of any energy system [60]. The basic incentive to use purchased electricity and life cycle cost as mentioned above in Section 4, as the main objective functions, is because these two factors are of main interest of the investors, contractors and also the end user to make decisions on any project, as discussed in earlier studies [58]. These two factors are conflicting in nature, which is needed in optimization problem and mathematically studied by Deb et al. [71]. Purchased electricity and life cycle costs are the objective functions. The higher the cost, less energy is needed to be purchased and vice versa. Another analysis indicator that can be used to evaluate the performance of the system can be the minimization of the emissions [59]; however, it is assumed that since the onsite energy is generated via solar energy, therefore, by lowering the purchased electricity via grid, the emissions would also be lowered. The emissions are not studied in the present paper and would be studied in the future work.

The other three additional factors used in the present study is simple payback period, renewable energy fraction (REF) and onsite energy fraction (OEF) and explained in the following sub-section. The motivation to these three factors is as follow. Firstly, the payback period is an important factor that is used by companies to make decisions regarding their future investments [81]. It is an effective tool that provides an effective value to the investment risk [81]. Moreover it is commonly used and understood by companies and academics together and provides a value to the project that can be easy communicated easily between the two entities. Secondly, solar fraction is another factor or indicator used generally by many researchers [15,82,48] in such concepts, which defines the amount of heat demand met via renewable sources. The solar fraction can also be defined as Renewable energy fraction (REF) [11]. The higher the fraction, higher is the technical performance of the energy system. Lastly, the onsite energy fraction (OEF) [60] is used because it provides the values which explain what part of the local demand is met by the locally produced energy (using renewable sources). The large the value, the better is the local utilization of the locally produced energy by the community. The main motivation behind building such solar communities is to make such districts self-sufficient, so that less energy is imported and which results in lower emissions and lower life cycles costs. All these values are also used by earlier studies to compare and evaluate the energy systems in addition to the objective functions [60,17] broadly, because it is simple and used in practice. Therefore, all these indicators are used in the present study to provide both the technical and financial health of the energy systems.

5.2. Simple payback period

The simple payback period is also calculated to analyse the time required for the amount invested by the company in the solar district heating systems to be repaid by the cash flows generated by the assets and the savings. This savings occurred due to renewable energy generation and self-consumption of the onsite generated energy, causing a reduction in the purchased electricity. Generally, investment with a shorter payback period is considered better, since the investor's initial investments are at risk for a shorter time. This provides the value after which the investors start getting the profits. The payback period is usually calculated in years [83]. It is calculated by dividing the investments by the savings and cash inflows. In the present study, the simple payback period includes the cost of the energy system. It does not include the cost of the building, as it is assumed that buildings are owned by the individual customer and of no interest for the energy system companies and investors.

5.3. Renewable energy fraction (REF)

The renewable energy fraction (REF) is also calculated to estimate the on-site energy fraction [60] of renewable energy utilization for heating. For heating, the renewable energy fraction is defined in Eq. (1), it is the ratio of renewable energy used to run the system and total heating demand of the system. In this method, the grid electricity (non-renewable) part is not included in the calculation in order to include only the renewable part to calculate the renewable energy fraction (REF_{heat}) [10]. The household appliances electricity demand is also not included in the calculations.

The renewable energy fraction for heating is defined as,

$$\begin{aligned}&\text{Renewable energy fraction heat (REFheat)}\\&= 1 - [(\text{HP+backup direct heating}\\&\quad +\text{pump) electricity consumption via grid per year}\\&\quad /(\text{SPH} + \text{DHW demand per year})],\end{aligned} \tag{1}$$

5.4. Onsite energy fraction (OEF)

The onsite energy fraction (OEF) is the value that defines the amount of the electrical demand covered by the onsite generation by the renewable source i.e. PV. In the present study grid electricity is used to import the electricity in order to meet the requirement of the electricity when there is shortage of electricity produced by the PV. The OEF is defined as the ratio of the purchased electricity and total demand electrical demand of the whole community [60]. It includes the

building appliances demand and energy system demand. Batteries are not included as the storage in the present study.

6. Results and discussion

To demonstrate the effectiveness and economic feasibility of the proposed decentralized photovoltaic based district heating system, the results of decentralized photovoltaic based district heating system are discussed and compared against:

Case 1) Decentralized photovoltaic based district heating system (DPV).

Case 2) Centralized photovoltaic based district heating system (CPV).

Case 3) Decentralized roof-mounted solar thermal collector based district heating system (DST).

Case 4) Centralized roof-mounted solar thermal collector based district heating system. (CST).

Case 5) Non-optimized reference case, single building system.

6.1. Multi-objective optimization

The non-dominated (optimal) solution of the decentralized photovoltaic based district heating system is shown in Fig. 7. For the comparison against the proposed decentralized photovoltaic based district heating system (DPV, case 1), the optimal results from the previous study on a similar centralized and decentralized solar thermal based heating system [17] and a centralized photovoltaic based heating system [10] are also presented in the results. In Fig. 7, the blue points are for the centralized solar thermal (case 4, CST), orange points are for the decentralized solar thermal (case 3, DST), green points are for the centralized photovoltaic (case 2, CPV) and purple points are for the decentralized photovoltaic (case 1, DPV) based district heating system. Lastly, the red square shows the reference building case.

Fig. 7 shows that there exists a wide range of optimal solutions, these solutions can be selected based on the customers' requirements. Purchased electricity is shown on the x-axis, while LCC is shown on the y-axis of the Fig. 7. The Fig. 7 shows that non-optimized reference case was worst compared to all the four community sized energy systems, in terms of both the objectives i.e., in the purchased electricity and in the LCC. The purchased electricity is 77 kW h/m^2/yr and the LCC is 379 €/m^2 for the non-optimized energy system. Therefore, for the future heating networks, the emphasis can be on the community-sized heating systems, instead of single-building energy systems. This allows reducing the LCC and also the purchased electricity.

Overall in Fig. 7, it is found that the decentralized photovoltaic based heating system, DPV (purple points, case 1) performed better than all the other systems. It clearly performed better than the centralized collector, CST (blue points, case 4) and the centralized photovoltaic, CPV (green points, case 2) based energy systems. However, in a few configurations, the decentralized collector, DST (orange points, case 3) is partly better than the decentralized photovoltaic, DPV (purple points, case 1). In Fig. 7, it can be observed that the imported electricity of the decentralized photovoltaic based heating system (purple points) reduced from 40 kW h/m^2/yr to 21 kW h/m^2/yr, and LCC changed from 157 €/m^2 to 359 €/m^2. By having a decentralized photovoltaic based energy system in the best performing configurations, the purchased energy can be reduced by 22% and the LCC can be reduced by 40% compared to the centralized solar thermal system. In other words, the decentralized photovoltaic based heating systems performed better in all the configurations than the other systems. Moreover, it performed better in the configurations where purchased electricity is less than in the decentralized solar thermal system.

Three phenomena can be observed in Fig. 7, especially when comparing photovoltaic based decentralized (case 1) and solar thermal based decentralized (case 3) systems. Firstly, in section 'a' of the front, it is observed that the photovoltaic based decentralized district heating system (purple point's case 1), the LCC is lower than the solar collector based decentralized district heating system (orange point's case 3) in Fig. 7. This is because in case 1, there is no collector and the photovoltaic costs are lower than the collector. Therefore in the worst technical performing configuration, the LCC is lower for the photovoltaic based decentralized system (case 1).

Secondly, as the Pareto front progresses from worst technical performing to best technical performing optimized configuration in section 'b', it is found that in the photovoltaic based system (case 1), relatively large investments are made in photovoltaic to reduce the purchased electricity. The system has to provide energy to both the air-water and water-water heat pumps to reduce the purchase electricity objective, therefore the LCC increases rapidly. On the other hand, for the collector based decentralized system (case 3), as the Pareto front progresses worst technical performing to best technical performing optimized configurations in section 'b', any small investments in both the collector and photovoltaic reduced the purchased electricity. Moreover, in case 3 there is no air-water heat pump and only water-water heat pump exists. Any less investments in the collector and photovoltaic area is enough to reduce the purchased electricity; therefore the LCC is slightly lower than in case 1 in the middle section 'b' of the Pareto front.

Lastly, in section 'c', as the investments on the collector and

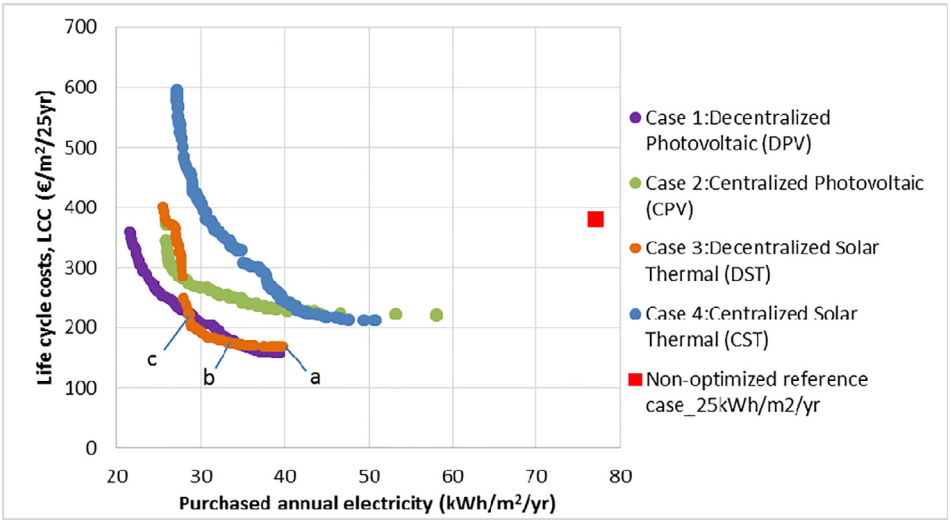

Fig. 7. Pareto fronts of the optimized centralized, decentralized energy systems (case 1, 2, 3 and 4) and non-optimized reference case.

photovoltaic starts to increase in collector based decentralized system (case 3), the LCC also increases; it is done by the algorithm to reduce the purchased electricity. This increase in the LCC caused the case 3 front to cross the front of the photovoltaic based decentralized system (case 1). This also shows that in the collector based decentralized system (case 3), the investments in the collector and photovoltaic are not enough to reduce the purchased electricity significantly in section 'c' of Fig. 7. This indicates that the control strategy of the solar thermal based decentralized system is not able to utilize the potential of the photovoltaics, as there is no strategy to utilize and store the onsite generated electricity by the photovoltaics in case 3. On the other hand, in a photovoltaic based decentralized system (case 1), in section 'c' it is observed that with an identical LCC compared to case 3, the purchased electricity is less or the technical performance is better. This is because in the photovoltaic based decentralized system (case 1), the electricity from the photovoltaic is stored in the tanks and seasonal storage in the form of heat and not exported. Therefore, the technical performance is better compared to case 3.

6.2. Technical performance analysis and payback period of the non-dominated solutions

To look at the economic feasibility from an energy investor's perspective, the payback period of the systems is introduced in Figs. 8 and 9. Fig. 8 shows that the centralized solar thermal based system has the higher payback period for all the optimized cases, where the minimum payback period is 17 years and the maximum payback period is 58 years. On the other hand, it can be observed that with the decentralized photovoltaic based heating system, both the payback period and the purchased electricity value can be reduced, compared to all the other systems. The minimum payback period is 9 years while the maximum payback period is 27 years. In other words, it can be concluded that with the decentralized photovoltaic based heating system (DPV, case 1), for a similar demand of the community, better technical performance can be achieved with better economic performance. This means that the investor would get the investment return in less than 9–27 years, depending on the optimized case selected. There are two reasons for this: 1) The cost of the photovoltaics is less compared to the collector; therefore the LCC is better in case 1 (DPV), where only photovoltaic is used instead of the expensive collector, causing a reduction in the payback period; 2) The solar energy from the photovoltaics is saved in the tanks in the form of heat instead of exporting it; therefore as a result, the purchased electricity is less.

The payback of the non-dominated optimized solutions in cases 1, 2, 3 and 4, against the renewable energy fraction are shown in Fig. 9. The (x-axis) of Fig. 9 shows the renewable energy fraction and the (y-axis) is the payback period. The renewable energy fraction for the reference system (around 40%) is clearly less than the REF for the other systems because the reference system has no solar facilities. This figure also shows that to achieve a higher renewable energy fraction for heating, renewable energy generation sources and storages are needed and focus should be on community scale system rather than single building solutions. However, by integrating renewable energy sources and storages, the payback period also increases, as shown in Fig. 9 and cases 1, 2, 3 and 4, but the REF_{heat} also improves compared to the reference case. It can be concluded that instead of investments in single building-heat pump solutions, investments should be made in community-sized solutions integrated with storages and renewable sources.

Overall the figures show that when the renewable energy fraction (more energy from renewable sources) gets high, the payback period gets high as well. This is because, in the cases where the renewable energy fraction is high, the investments in the system are high. If the comparison is done among cases 1, 2, 3 and 4, it can be found that the centralized solar thermal based system has the higher pay back period for all the optimized cases, where the minimum payback period is 17 years and the maximum payback period is 58 years. Centralized solar thermal based heating system (CST, case 4) has a higher payback period for the cases with a higher renewable energy fraction due to the fact that large number collectors are needed to achieve higher fractions. These collectors are expensive compared to the photovoltaics. Therefore, as a result the payback period is higher compared to the photovoltaic based heating systems. It was also found that the photovoltaic based decentralized system (DPV, case 1) has the lowest maximum payback period (i.e. around 27 years) with the highest renewable energy fraction for heating (REF_{heat}) (i.e. around 99%) compared to all the other systems (case 2, 3 and 4). In the photovoltaic based decentralize energy system (case 1), the payback period can be lower than 10 years, with REF_{heat} around 70%, which is even lower than the reference case payback period, i.e. around 16 years. This means that the investor would realize investments returns in less than 9–27 years, depending on the optimized case selected, in some cases even earlier than the reference case. Therefore, it can be concluded that the proposed photovoltaic based decentralized system (case 1) has the lowest payback with better performance. However, in such cases where the payback period is low, the renewable energy fraction is not so high.

It is also observed in Fig. 9 that among all the energy systems, usually the solar thermal based energy systems' (cases 3 and 4) payback period gradients are steep at the higher renewable energy fraction (REF_{heat}) section. This is because of the increase in the collector area in the best performing cases with higher REF_{heat}. The cost of the collector is generally higher compared to the photovoltaic cost (Table 3). Therefore in solar thermal systems, when investments are made in the

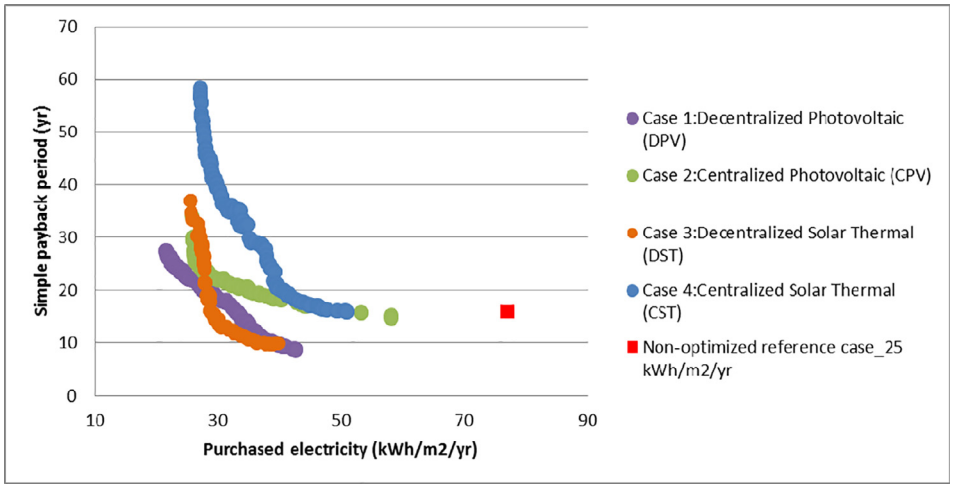

Fig. 8. Comparison between the simple payback period vs. purchased electricity of the energy systems (DPV, CPV, DST, and CST) and non-optimized reference case.

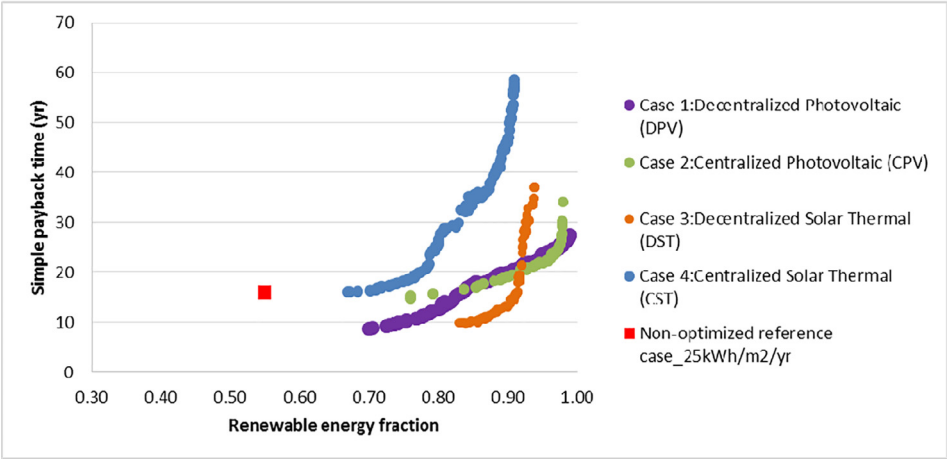

Fig. 9. Comparison between the simple payback period vs. the renewable energy fractions of the energy systems (DPV, CPV, DST and CST) and non-optimized reference case.

collectors, the rise in the investments are large, resulting in larger paybacks compared to the photovoltaic based energy systems (case 1 and 2). In photovoltaic systems (case 1 and 2), the cost of the photovoltaics are generally lower than the collector, resulting in a lower payback period and resulting in less steep gradients in the payback period curves in Fig. 9. An extremely steep gradient is observed in the last few configurations near the high renewable energy fraction (RE-F_{heat}) section of the photovoltaic based centralized system (case 2). It is due to increase in the seasonal storage volume, tank volume and photovoltaic area in the last few cases compared to the photovoltaic based decentralized system (case 1).

6.3. Comparison of the design variables in the Pareto optimal solutions

For reference, the best and worst Pareto fronts in Fig. 7 are selected for further analysis and comparison between the design variables. The worst case is the roof-mounted centralized solar thermal system (CST) and the best case is the decentralized photovoltaic based heating system (DPV) as proposed in this study. Both Figs. 10 and 11 show the comparison of the design variable costs of the Pareto optimal solutions for the centralized solar thermal and decentralized photovoltaic systems, respectively.

It can be observed in Fig. 10 (case 4, CST) that the solar thermal collector and the photovoltaic are the largest portion of the investments for the centralized system in (configuration 1). On the other hand in (configuration 141), the collector forms the largest portion of the investment. In Fig. 10 the performance of the centralized solar thermal system improves when the investments are made in the collector, photovoltaics and in the building efficiency as the solution moves from (configuration 141 to 1). The algorithm initially increases the photovoltaic area due to low cost, compared to the collector. The investments are also made in the buildings and collector area, which further allows reducing the purchased electricity of the system. The volume of the borehole seasonal storage also increases with the increase in the collector area from (configuration 141) to (configuration 1) in Fig. 10. The OEF value ranged from 11% to 40% from configuration 141 to 1 in Fig. 10.

Fig. 11 shows that in the photovoltaic based decentralized (case 1, DPV) system contained photovoltaic panels as largest portion of the investments in all the configurations. Buildings and storage cost also formed significant part of the investment in the configuration 1 in Fig. 11. In Fig. 11, photovoltaic panels area are initial increased followed by the improvement in the buildings efficiency, warm tanks volume and number of heat pump, to further improve the performance of the energy system (case 1), as the solutions progresses from configuration 195 to 1. Overall, photovoltaic panels, heating demand and storage are important design variables in photovoltaic based decentralized system.

Large photovoltaic panel area, large volume of the short-term tanks and seasonal storage and large number of heat pumps reduced the amount of purchased electricity to around 21 kW h/m^2/yr. PV is given priority in this energy system (case 1) because it is the main source of energy generation of the heat via the heat pump. The renewable energy fraction for heating in case 1 varied between 99% and 60%. The OEF value ranged from 36% to 75% from configuration 195 to 1 in Fig. 11.

Both the Figs. 10 and 11 shows the similar trends. The performance

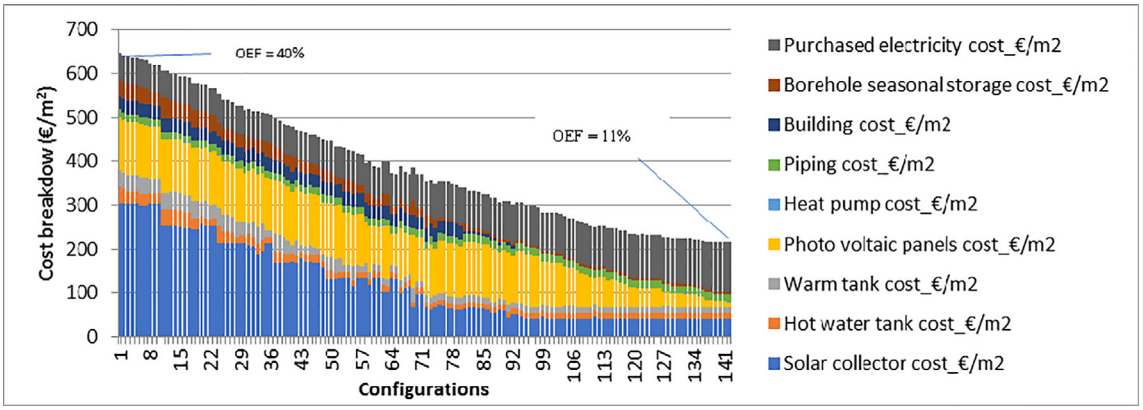

Fig. 10. Design variables cost in the Pareto optimal solutions of the centralized roof-mounted collector based district heating system (case 4, CST).

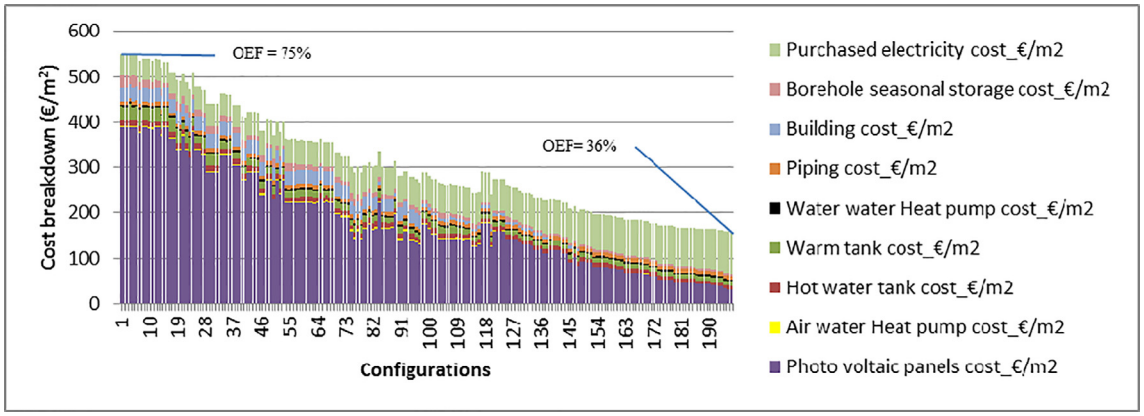

Fig. 11. Design variables cost in the Pareto optimal solutions of the decentralized photovoltaic based district heating system (case 1, DPV).

Table 4
Design variables values range of the decentralized photovoltaic based heating system (Case 1, DPV) and centralized roof-mounted solar thermal based heating system (Case 4, CST).

Design variable	DPV, Case 1		CST, Case 4	
	Best optimal configuration 1	Worst optimal configuration 195	Best optimal configuration 1	Worst optimal configuration 141
PV area (m^2)	19,162	1630	5837	600
Roof-mounted ST area (m^2)	0	0	5408	500
BTES volume (m^3)	23,000	10,000	38,509	15,000
Number of BTES	442	11	323	9
Hot tank volume (m^3)	135	100	473	150
Warm tank volume (m^3)	480	120	474	150
Number of air-water heat pump	78	6	0	0
Building demand (kW h/m^2/yr)	25	50	25	50

of the system improves with the increase in the investments on different design variables, in both the roof-mounted solar thermal centralized based system (case 4-CST, Fig. 10) and the photovoltaic based decentralized system (case 1-DPV, Fig. 11).

Nevertheless, there are five differences between the roof-mounted solar thermal centralized based system (case 4, CST) in Fig. 10 and the photovoltaic based decentralized system (case 1, DPV) in Fig. 11. These differences are as follows:

1) The minimum purchased electricity is 27 kW h/m^2/yr, with a 91% renewable energy fraction for the roof-mounted solar thermal centralized based system (case 4, CST), and the minimum purchased electricity is 21 kW h/m^2/yr with a 99% renewable energy fraction for a photovoltaic based decentralized system (case 1, DPV).
2) While comparing the roof-mounted solar thermal centralized based system (case 4, CST) in Fig. 10 and the photovoltaic based decentralized system (case 1, DPV) in Fig. 11, the solar collector cost exists in the optimized configurations in case 4 (Fig. 10). On the other hand in case 1, photovoltaic is used as the main component to produce heat, and there is no collector at all in this system. This means that the collector can be replaced completely by the photovoltaic to provide heat energy to the system. In the photovoltaic based decentralized system (case 1, Fig. 11), higher investments are made in the photovoltaic, because this is the main source for producing electricity and heat. Moreover, in this system (case 1) the water-water and air-water heat pumps need electricity, which is provided via photovoltaics.
3) In the photovoltaic based decentralized system (case 1, Fig. 11), the BTES cost is slightly lower than the roof-mounted solar thermal based centralized system (case 4, Fig. 10) in configuration 1. This is because in the solar thermal based centralized system, seasonal storage is charged by the hot tank at a higher temperature. Therefore, to retain energy over the season, a large volume is required.
4) The photovoltaic based decentralize system (DPV), has higher OEF compared to the CST system because in the DPV system the excess electricity from the PV is stored in the tanks and seasonal storage in the form of heat, that increases the OEF of the system. On the other hand in CST system the excess electricity is directly sold to the grid.
5) Lastly, the cost of the warm tank in the best performing configuration 1 of the roof-mounted solar thermal based centralized system (case 4, Fig. 10) is lower compared to the photovoltaic based decentralized system (case 1, Fig. 11). It corresponds that the larger size of the warm tank is needed in the photovoltaic based decentralized system in case 4 to achieve better performance, as decentralized heat pumps use this as a heat source.

The photovoltaic based district heating system (Case 1, DPV) outperformed the other systems. For comparison between the design variables values of the worst and best performing optimized configurations, the best energy system i.e. case 1, DPV and the worst energy system i.e. case 4, CST systems are shows in Table 4 as a reference. These are the extreme design variables values (of the worst and best configurations) in the optimized solutions that are present in Pareto front in Fig. 7. As all the configurations in the Pareto front in Fig. 7 are optimal solutions, and represent wide range of solutions. Therefore any solution can be selected from the Pareto front based on the decision maker selection criteria. It can be observed that, PV area, BTES volume, heat pumps and building performance increases in order to improve the technical performance of both the DPV and CST. As a consequence the LCC would also increase depending on the investments done on the different components.

7. Conclusions

Photovoltaic based decentralized district heating system simulation model is developed and optimized in the study. Dynamic simulation

software is used to simulate the system. Later on, the model is also optimized using Non-dominated Sorting Genetic Algorithm (NSGA-II). Two objectives that are minimized in this study are purchased electricity and life cycle cost of the proposed system. To compare the technical and economic performance of the proposed photovoltaic based decentralized heating system, three different optimized and new types of solar district systems and a non-optimized single reference building heating system are used. All the systems are compared against the purchased electricity, life cycle costs, payback period and renewable energy fractions. Here is a short summary of the significant findings:

- In general, the proposed photovoltaic based decentralized district heating system performs better than the single heat pump heated building (non-optimized reference case). The technical performance (purchased electricity/REF) of the optimized system (case 1, DPV) is better than the reference case.
- The photovoltaic based decentralized system (Case 1, DPV) and its control strategy performed better than the other systems.
- The purchased electricity of the photovoltaic based decentralized system (Case 1, DPV) can be reduced by 22%, and life cycle cost by 40% compared to the roof-mounted solar thermal based centralized system (Case 4, CST). The worst performing energy system is the solar thermal based centralized system.
- The purchased energy of the photovoltaic based decentralized system (Case 1, DPV) varied from 40 kW h/m^2/yr to 21 kW h/m^2/yr while the life cycle cost varied from 157 €/m^2 to 360 €/m^2. The renewable fraction (REF_{heat}) varied from 60% to 99%. The OEF varied from 36% to 75%.
- The best performing photovoltaic based decentralized system (Case 1, DPV) has a payback period of 9–27 year, compared to the worst performing roof-mounted collector-based centralized system (Case 4, CST) has a payback period of 17–58 years. Therefore, it is possible to get the investments back in less than 10 years in the photovoltaic based decentralized system without incentives or benefits provided by the government.
- In the best performing photovoltaic based decentralized system (Case 1, DPV), the borehole thermal energy storage, warm tank and photovoltaic size increases to reduce the purchased electricity. However, the life cycle cost and payback period also increases.

The study revealed that the community sized district heating systems performed better compared to the single building solutions. The self-consumption of the energy is always better than exporting it. The self-consumption can be increased by integrating seasonal storage in the system, this allows reducing the importing of electricity from the grid. The study also showed that novel approach of integrating photovoltaics and seasonal storage together in the district heating systems can reduce the purchased electricity, payback period and life cycle cost compared to solar thermal collector based energy system.

The study can be used to design and implement a real pilot project in Nordic countries. This study is a simulation based analysis, and in the future it is planned to perform experimental validation. As no such solar district heating system exist in Finland, this study can act as a modelled based reference system. As there is no real solar community in Finland, therefore it is difficult to compare the outcomes of the study and the scope of the study is limited to the simulation studies. However, the implementation of the pilot project at Drake Landing solar community (DLSC), Canada shows that such concepts can be built in cold climatic conditions with high renewable energy fraction. By introducing photovoltaics (PV) as the main source of the energy generation and heating, the novel decentralized PV based heating system can be built with lower life cycle costs, lower payback period and at the same time high performing compared to solar collector based heating systems at the community scale as shown in the present study. In order to realize these systems in real application, seasonal storage and price reduction of the components, would play an important role. Another challenge in building real applications of these systems is simulations and modelling issues. It is important to provide improved simulation and optimization methods. At the moment, the computation time and costs are significantly high, especially, if the design variables, multi-criteria objectives and simulation models are integrated together for building and analysing such systems. Therefore, it is necessary to build good simulation and optimization methods for example machine learning methods with NSGA-II algorithm, because this would provide a suitable approach and cheap methods to solve this issue. The appropriate simulation and optimization methods and models are needed to create data and models for building real solar communities around the world.

The scope of the present study is limited to the comparison between the solar thermal based district heating systems and photovoltaic based district heating systems. As the photovoltaic based district heating system clearly outperformed the solar thermal based energy systems both in technical and financial aspect. Therefore in the future it is planned to perform experimentation and measure the performance based on costs, technical performance and emissions.

Overall, the issue of climate change can be addressed by building such community based energy systems. Policies and incentives shall be designed that can promote such concepts around the world. With the increase in the demand of the collectors and photovoltaics, it is expected that the costs of these components would reduce. This would ultimately benefit the district heating business and would also make them competitive compared to the traditional district heating systems.

Conflict of interest

None.

CRediT authorship contribution statement

Hassam ur Rehman: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing - original draft, Writing - review & editing. **Janne Hirvonen:** Conceptualization, Data curation, Formal analysis, Methodology, Validation, Visualization, Writing - review & editing. **Risto Kosonen:** Funding acquisition, Project administration, Resources, Supervision. **Kai Sirén:** Conceptualization, Formal analysis, Funding acquisition, Project administration, Resources, Supervision, Validation, Visualization, Writing - review & editing.

Acknowledgements

The study is supported by the Academy of Finland, Finland, grant number: 284977, EES (energy efficiency systems) group Aalto University, Finland and K.V. Lindholms stiftelse, Finland. The funding bodies had no such involvement in preparing the manuscript, methods and results etc.

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